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**Research paper**

# Settlement of a historic building due to seepage-induced soil deformation

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**Abstract:** The research paper reviews issues associated with the impact of groundwater flow on soil characteristics and parameters, hence, the entire structure of a building set on it. Water seepage through the ground, building subsoil or structural elements of buildings made of soil affects the soil skeleton and may lead to changes in the arrangement of individual grains relative to each other, i.e., a modified soil structure. Soil solid phase (soil skeleton) deformations resulting from seepage forces are called seepage-induced deformations. The article characterizes typical seepage-induced deformations and specifies a criterion defining the beginning of the phenomenon. The case study involved using data on cracks and deformations in a historic building, as well as water seepage in its subsoil. Seepage was analysed, and zones where the seepage process initiation criterion was exceeded, were determined based on subsoil water level monitoring data. The determined zones coincide with the location of building cracks and scratches and confirm the possible cause behind building damage.

**Keywords:** building subsoil, seepage in the ground, settlement of building, seepage-induced deformation

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# 1. Introduction

Water seepage through the ground, building subsoil or structural elements of buildings made of soil affects the soil skeleton and may lead to changes in the arrangement of individual grains relative to each other, i.e., a modified soil structure [1–3]. Soil solid phase (soil skeleton) deformation resulting from seepage forces are called seepage-induced deformations. Such phenomena occur not only in hydrotechnical structures, but also in the subsoil of other buildings in cities and highly urbanized environments [4–6]. They also apply to the subsoil of historic buildings, where they usually significantly impact the condition of their structural elements [7].

An accurate technical assessment of building condition as a whole is an issue that requires professional experience [8–11], while the evaluation of the technical condition of historic buildings is one of the most difficult tasks in civil engineering [12–21]. This results directly from the specificity of such facilities, the execution of which involved often currently obsolete construction technologies and natural materials, such as stone, lime, clay, wood and reed.

The reconnaissance of the structural system of historic buildings, including religious, cannot be limited only to assessing the changing strength parameters of the materials themselves, and evaluating the structural systems that were used to erect such buildings [22–26], but must also involve the parameters of the subsoil the structure is set on. The assessment of changes in the subsoil parameters requires special consideration of the impact of numerous external factors on the changes of the water and soil conditions in the subsoil, which result from the particular location of the buildings. Changes in the development of urban space – urbanized areas, which involves the construction of infrastructural networks or road pavement compaction in the immediate and more distant vicinity of new buildings, often with a multi-storey underground section, entail changes in the hydrology of urbanized areas and groundwater levels [6]. Changes in the groundwater levels may lead to changed parameters of the structural elements used to execute the underground part of the building, as well as the geotechnical parameters of the subsoil the building is set on [7, 27, 28]. The number of factors affecting building and subsoil parameter changes make the reconnaissance and diagnostics of their technical condition an extremely difficult engineering tasks [29].

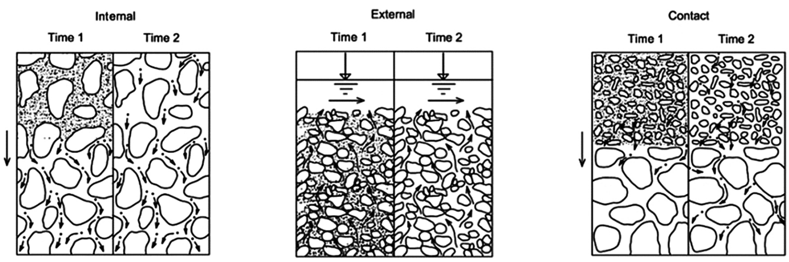
# 2. Soil seepage-induced deformation characteristics

When it comes to design studies related to historic buildings, civil engineers must work in teams consisting of specialists dealing with general construction, masonry, and wooden structures in particular, as well as geotechnical specialists.

The mechanical impact of seepage forces on the soil skeleton may lead to its deformations. Soil, solid phase deformations caused by the action of seepage forces are called seepage-induced deformations or local seepage strains [30]. Seepage-induced deformations usually cover small soil masses (grain, particle or lump displacements) and result in changes of soil condition and internal structure, hence, its parameters.

Seepage-induced deformations resulting from the displacement of individual soil grains and particles regardless of each other and under the influence of seepage forces can be called microdeformations. Such seepage-induced deformations are particularly frequent in non-cohesive soils.

Generally, the creation of seepage-induced deformations and their development are usually very complex and depend on numerous factors. Therefore pure-form seepage-induced deformations can be observed very rarely [29]. Seepage-induced deformations can have different causes, while the source literature often calls their causative factor as seepage-induced deformations, one terms applies to various processes or phenomena, or the same process or phenomenon is called differently [29]. Seepage-induced deformations are called different names. The most frequent ones include uplift [29], quicksand [29], hydraulic piping [27, 31], suffosion [29], erosion [29] and silting-up [27]. In addition, the latter three, owing to the nature of the phenomenon, are described using such adjectives as internal, external or contact. Fig. 1a shows a diagram of internal suffosion, Fig. 1b shows external suffosion, while Fig. 1c shows contact suffosion. Erosion is also divided into internal (Fig. 2a), external (Fig. 2b) and contact (Fig. 2c). Fig. 2d shows the most dangerous phenomenon – hydraulic piping [27]. The phenomena induced by the mechanical impact of water on the soil skeleton may lead to excessive settlement and, consequently, to a construction failure or even disaster [27].




(a) (b) (c)

Fig. 1. Types of suffusion: a) internal, b) external, c) contact [32]

The occurrence of a given deformation type will depend on [27]:

– nature of the phenomenon [29]: soil grain and particle displacement regardless of each other (microdeformations) or the displacement of a large volume of soil under the impact of seepage forces or uplift (macrodeformations),
– type of soil in terms of cohesion [27, 33, 34]: cohesive or non-cohesive,
– type of soil medium [27,35]: homogeneous (built of a single soil type, the graining of which in various point of the volume is described by the same grain size curve, i.e., is characterized by the same granulometric composition) or layered (built of at least two different homogeneous soil layers, each of which has the same granulometric composition at various points within its volume, i.e. grain size curves are identical, with these soils being soils of different graining relative to each other, i.e., grain size curve characterizing these soils are different),

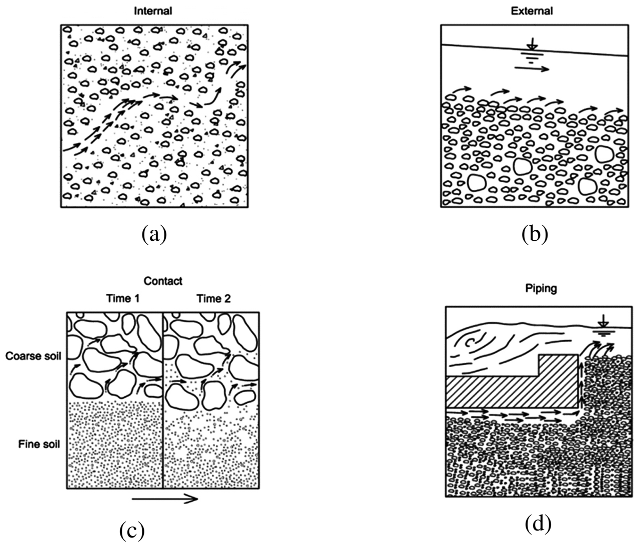



Fig. 2. Types of erosion: a) internal, b) external, c) contact, d) hydraulic piping [32]

- phenomenon location within the soil volume in question [27]: inside, on the surface, within a crevice in the soil medium or interbedding, in the contact zone between the soil and the concrete element of the building or in the contact zone between two soil layers,
- soil type in terms of varying granularity [27,35]: sorted (built of particles and grains of the same size) and unsorted (built of grains and particles of different size),
- water flow direction relative to Earth's gravity [27]: vertical up, vertical down or horizontal,
- flow direction relative to layer surface [27]: perpendicular to the layer surface or parallel to the layer surface.

It should be noted that an unsorted soil is a suffosive soil, i.e., different grains and particles can be transported out of its volume under given seepage conditions. The concept of soil suffosiveness is relative, since it depends on load conditions and seepage gradients. The phenomenon of suffosion (suffosive soil) can occur under relatively low vertical loads on the soil and relatively high hydraulic gradients, and the phenomenon might not occur under relatively high loads and low hydraulic gradients, as is the case with a non-suffosive soil. An ideal non-suffosive soil is a sorted soil, built of particles (grains) with uniform sizes (graining uniformity coefficient $C_U = 1.0$).

The conditions for the occurrence of seepage-induced deformations are often described by a critical gradient or critical rate value, i.e., a hydraulic criterion (sufficient condition) relative to the soil volume unit, within which a given phenomenon is observed for a given gradient or rate [31,38].

Water flow within a soil medium is induced by the difference in pressure between the initial point and the end point of the water molecule seepage path. Seepage direction is consistent with seepage forces acting on the soil volume unit. Seepage forces generally tend to displace the soil towards flowing water along its entire considered volume, and the so-called run-off pressure $j_v$ can be secluded.

Run-off pressure $j_v$, also called hydrodynamic pressure is the pressure applied on the soil skeleton and water, which balances the water-soil particle friction forces, relative to the soil volume unit. [30]

$$j_v = \gamma_w \cdot i \tag{2.1}$$

where: $i$ – means the seepage pressure gradient, $\gamma_w$ – means the water specific gravity.

The seepage pressure gradient is a ratio of pressure losses along the seepage section $\Delta h_f$ and the seepage path length $\Delta s$.

$$i = \frac{\Delta h_f}{\Delta s} \tag{2.2}$$

According to [36], the gradients of seepage pressure occurring in the subsoil of all hydrotechnical structures and within the earth dam body should satisfy the relationship:

$$\gamma_i \cdot i \leq i_{kr} \tag{2.3}$$

where: $i$ – means the seepage pressure gradient, $i_{kr}$ – means the critical gradient values for a given soil, $\gamma_i$ – means the confidence factor, which, irrespective of the building class, is:

$\gamma_i = 1.5$ for a basic load system,

$\gamma_i = 1.3$ for a unique load system.

The aforementioned assumptions can also be adopted equally for other buildings and structures set on a subsoil that experiences seepage pressure gradients.

The values $i_{kr}$ can be determined using for example the Bligh method [37, 38] for the underground building or structure contour, by matching the $C_B$ coefficient, which depends on the soil type and by determining the $i_{kr}$ critical gradient as an inverse to the $C_B$ coefficient:

$$i_{kr} = \frac{1}{C_B} \tag{2.4}$$

Coefficient values for all subsoil types are listed in Table 1.

Table 1. Bligh coefficients and critical seepage gradients, depending on the subsoil soil type [37]

| Soil type | Bligh coefficient $C_B$ [–] | $i_{kr}$ [%] |
|---|---|---|
| Very fine sand, silts | 18.0 | 5.5 |
| Fine sand | 15.0 | 6.6 |
| Coarse sand | 12.0 | 8.3 |
| Fine-grain gravel | 9.0 | 11.1 |
| Medium-grain gravel | 5.0 | 20.0 |

Exceeding the critical seepage pressure gradient for a given soil, which is the loss of soil seepage resistance may lead to seepage-induced deformations. This may especially occur in varied-grained soils, where finer particles and grains may be lifted and displaced according to the seepage direction, resulting in the change of the original soil skeleton density, thus leading to its deformation (settlement, uplift or piping).

## 3. Soil seepage-induced deformations within the area of the St. Nicholas basilica in Gdańsk – case study

### 3.1. Technical condition characteristics

Up until the autumn of 2018, the Basilica building was in a satisfactory technical condition, approximately corresponding to its period of operation – the building was undergoing gradual renovation and restoration work. The main structural elements of the Basilica building did not exhibit any damage traces indicating significantly exceeded Ultimate Limit State (SGN) and Serviceability Limit State (SLS) conditions.

Disturbing damage to the vault over the southern aisle was observed in autumn of 2018, at the end of October. Intense (in terms of number and opening width) scratches of the squinches and deformations (buckling relative to the vault plane) of the ribs were identified during a thorough inspection.

Vault ribs were cracked with a displacement and detached from the squinch surface, and the opening width reached 6–8 mm. Arch wall crack (crevice with a mutual edge shift) between the second and third pillar of the southern aisle, with a maximum opening width of 28 mm was identified. Fig. 3 shows damage concentration in the southern aisle pillar area and the cracks of wall elements.

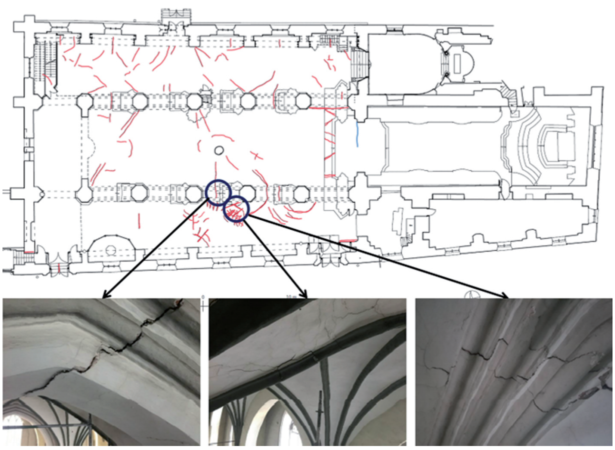


Fig. 3. Simplified stock-taking of Basilica southern aisle damage [43]

### 3.2. Scope of soil seepage measurements

Extensive diagnostics [39–43], typical for historic buildings situated within a dense urban development, which covered the Basilica and its adjacent area, involved also detailed soil testing and the installation of piezometers for observing water levels in the subsoil. Locations of test boreholes and implemented piezometers are shown in Fig. 4.

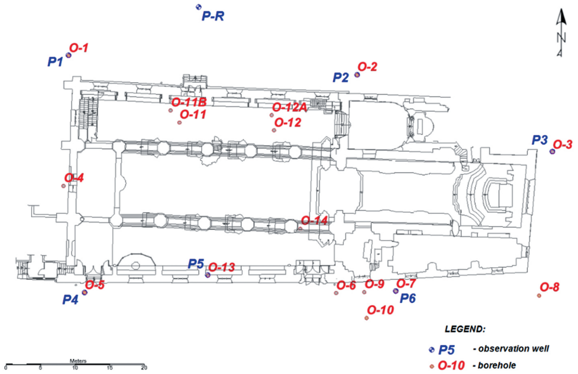



Fig. 4. Location of subsoil test boreholes and groundwater level observation piezometers [40]

The piezometers were located around the temple with cyclical observations conducted. The measured water table levels are listed in Table 2.

The types of soil in the subsoil and their resistance to the action of seeping water were determined based on the conducted geotechnical studies. The piezometers measured water levels were used to develop a map of water level distribution within the Basilica subsoil and the seepage direction. Fig. 5 shows the groundwater table map for

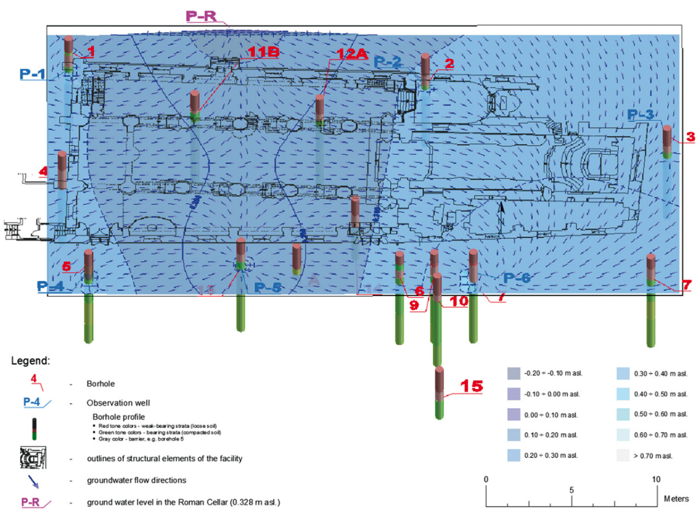



Fig. 5. Groundwater table level map with marked soil profiles at the borehole and piezometer location, with seepage directions for 31/7/2019, against the background of the Basilica basement level plan

Table 2. List of groundwater table measurements using piezometers located around the Basilica building – values in m a.s.l.

| Date | Observation well | | | | | | |
|---|---|---|---|---|---|---|---|
| | P1 | P2 | P3 | P4 | P5 | P6 | P-R |
| 02.07.2019 | 0.39 | 0.34 | 0.41 | 0.41 | 0.43 | 0.47 | 0.328 |
| 12.07.2019 | 0.49 | 0.60 | 0.36 | 0.46 | 0.04 | 0.56 | 0.328 |
| 20.07.2019 | 0.44 | 0.51 | 0.39 | 0.47 | 0.05 | 0.54 | 0.328 |
| 31.07.2019 | 0.41 | 0.38 | 0.33 | 0.43 | 0.03 | 0.49 | 0.328 |
| 01.10.2019 | 0.44 | 0.41 | – | 0.38 | 0.10 | 0.49 | 0.328 |
| 05.11.2019 | 0.57 | 0.45 | – | 0.37 | 0.22 | 0.55 | 0.328 |
| 19.11.2019 | 0.61 | 0.51 | – | 0.66 | 0.20 | 0.19 | 0.328 |
| 02.12.2019 | 0.59 | 0.50 | – | 0.52 | 0.19 | 2.93 | 0.328 |
| 03.02.2020 | 0.68 | 0.68 | 0.79 | 0.48 | 0.38 | – | 0.328 |
| 05.05.2020 | 0.94 | 0.86 | 0.84 | 0.98 | 0.60 | 0.99 | 0.328 |
| 08.05.2020 | 0.94 | 0.86 | 0.84 | 0.98 | 0.60 | 0.99 | 0.328 |
| 12.05.2020 | 0.94 | 0.91 | 0.89 | 0.98 | 0.6 | 1.34 | – |
| 13.05.2020 | 0.89 | 0.91 | 0.89 | 0.98 | 0.6 | 1.29 | – |
| 15.05.2020 | 0.94 | 0.86 | 0.89 | 0.98 | 0.6 | 1.14 | – |
| 18.05.2020 | 0.89 | 0.81 | 0.89 | 0.93 | 0.6 | – | – |
| 19.05.2020 | 0.89 | 0.81 | 0.79 | 0.98 | 0.6 | – | – |
| 20.05.2020 | 0.94 | 0.86 | 0.84 | 0.98 | 0.6 | – | – |
| 21.05.2020 | 0.94 | 0.86 | 0.89 | 0.98 | 0.5 | – | – |
| 22.05.2020 | 0.94 | 0.86 | 0.89 | 0.98 | 0.6 | – | – |
| 25.05.2020 | 0.94 | 0.86 | 0.84 | 0.98 | 0.6 | – | – |
| 26.05.2020 | 0.94 | 0.86 | 0.84 | 0.98 | 0.6 | 1.74 | – |
| 27.05.2020 | 0.94 | 0.86 | 0.84 | 0.98 | 0.6 | 1.74 | – |

31/7/2019, against the background of the Basilica basement level plan, with marked soil profiles in test boreholes and piezometers. Fig. 5 also shows water seepage directions resulting from piezometer groundwater levels. The analysis covered changing water levels on individual piezometers, as well as varying water seepage directions and seepage gradient values. Gradient values were analysed both along the entire length between the piezometers and locally, e.g., in the area of the pillars that experienced the greatest settlement.

Groundwater table level map for 2/12/2019 with seepage directions, against the background of the Basilica basement level plan is shown in Fig. 6.

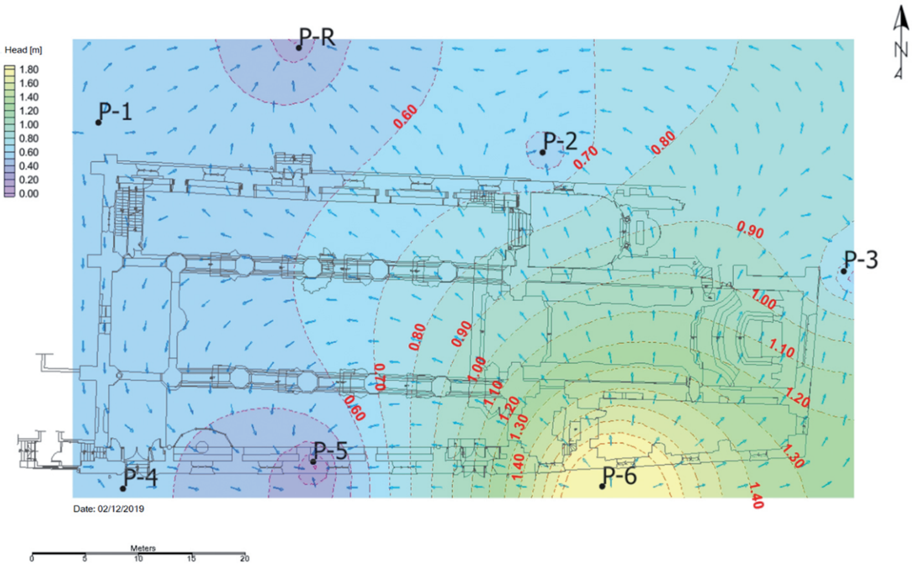
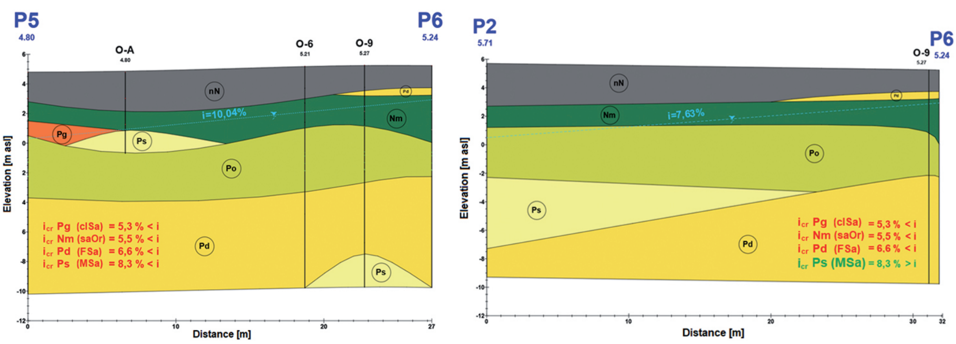



Fig. 6. Groundwater table level map with seepage directions for 2/12/2019, against the background of the Basilica basement level plan

Fig. 7a shows the P5-P6 longitudinal profile and the position of the groundwater table curve position on 2/12/2019, and Fig. 7b shows the P2-P6 longitudinal profile and the position of the groundwater table curve position on 2/12/2019. Fig. 8 shows the P5-P2 longitudinal profile and the position of the groundwater table mean curve position and the local mean curve on 12/7/2019, as well as a diagram of pillar foundation level. Fig. 7–8 also show determined mean gradients between piezometers, relative to the critical gradients for




(a) (b)

Fig. 7. Averaged groundwater table position within the Basilica area for 2/12/2019: a) P5-P6 longitudinal profile, b) P2-P6 longitudinal profile

given soil types. Red colour marks the soils with exceeded critical gradient values (Bligh criterion) [37].

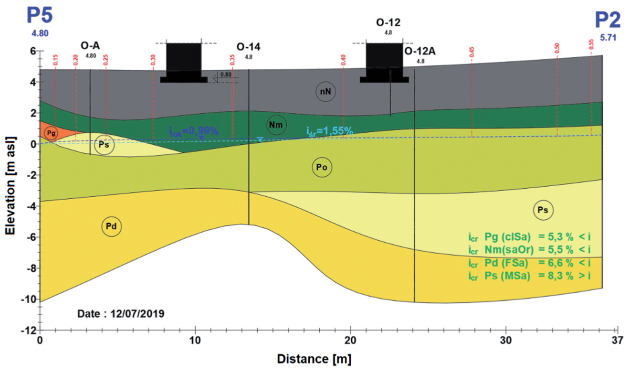



Fig. 8. Averaged groundwater table position and local table change within the Basilica foundation area for 12/7/2019 – P5-P2 longitudinal profile

Determined mean gradient values along the entire section between all piezometers are listed in Table 3. Changing cell colour intensity marks the maximum (intensive red and blue) and minimum (white cells) gradient values for soils found in the Basilica subsoil.

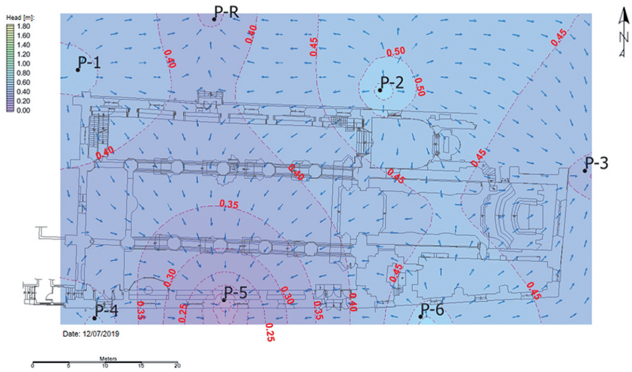
Table 3. List of mean hydraulic gradient values between individual piezometers and piezometer no. 6 for selected measurement periods using piezometers located around the Basilica building

| Obs. well no. | Direction | Slopes | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | 02.07. 2019 | 31.07. 2019 | 01.10. 2019 | 19.11. 2019 | 02.12. 2019 | 05.05. 2020 | 26.05. 2020 |
| P6 | P1 | 0.14% | 0.14% | 0.09% | –0.72% | 4.01% | 0.09% | 1.37% |
| | P2 | 0.41% | 0.35% | 0.25% | –1.01% | 7.63% | 0.41% | 2.76% |
| | P3 | 0.20% | 0.53% | l.d. | l.d. | l.d. | 0.49% | 2.96% |
| | P4 | 0.13% | 0.13% | 0.24% | –1.04% | 5.36% | 0.02% | 1.69% |
| | P5 | 0.15% | 1.68% | 1.43% | –0.04% | 10.04% | 1.43% | 4.18% |
| | P-R | 0.28% | 0.32% | 0.32% | –0.28% | 5.20% | 1.32% | l.d. |

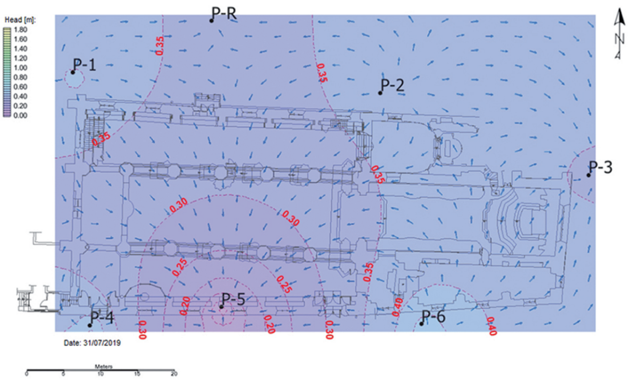
Note: l.d. – lack of data

Fig. 9 and 10 show a groundwater table level map with seepage directions for several sample measurement days. The results depict how water levels and seepage directions in the Basilica subsoil change.

Subsequent Figs. 11 and 12 show a map of hydraulic gradients – declines in the groundwater table level with seepage directions, for several sample measurement days.



(a)



(b)

Fig. 9. Groundwater table level map with seepage directions for a) 12/7/2019 and b) 31/7/2019, against the background of the Basilica basement level plan

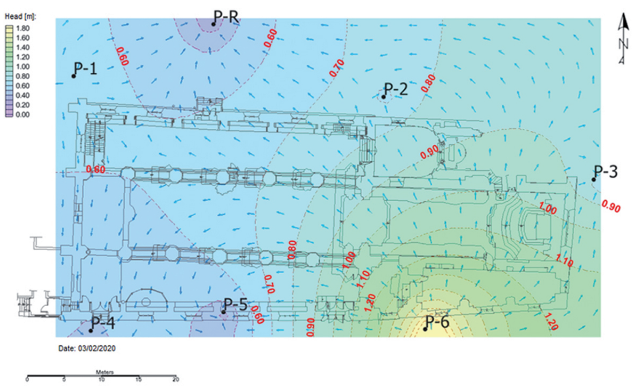
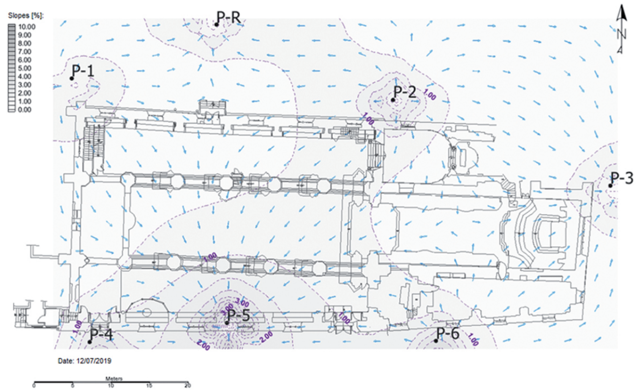
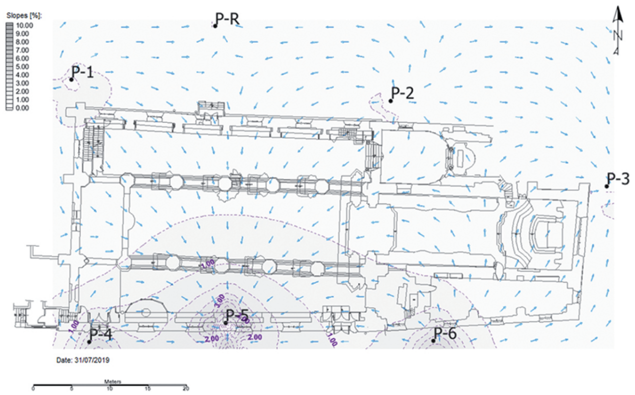


Fig. 10. Groundwater table level map with seepage directions for 3/2/2020, against the background of the Basilica basement level plan




(a)




(b)

Fig. 11. Map of local groundwater table declines with seepage directions for a) 12/7/2019 and b) 31/7/2020, against the background of the Basilica basement level plan

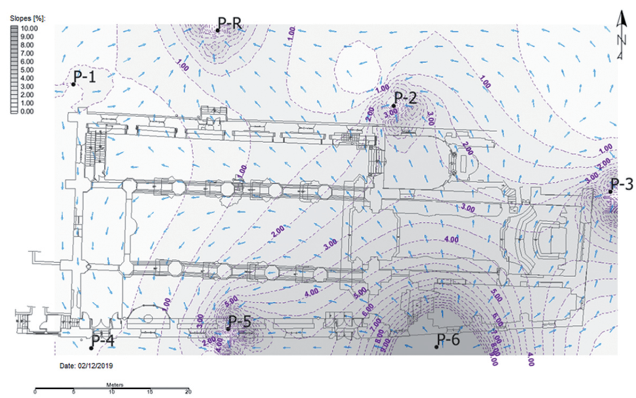



Fig. 12. Map of local groundwater table declines with seepage directions for 2/12/2019, against the background of the Basilica basement level plan

### 3.3. Analysis of soil seepage measurements

The presented results show how local declines in the Basilica area subsoil change. It can be clearly seen that the phenomenon varies over time, but qualitatively similar situations occur, such as on 2/12/2019 and 3/2/2020. The cyclical changes in the Basilica subsoil hydraulic gradients can initiate the formation of seepage-induced deformations. These changes can have various location, and the detachment of the subsoil from the Basilica floor was also found in several places.

The standard [44] describes the Ultimate Limit State (ULS) relative to the hydraulic uplifting of soil particles, internal erosion and hydraulic piping (HYD) in terms of failure caused by water flowing through a soil medium – understood as failure caused by the occurrence of run-off pressure, suffosion, silting-up, erosion or hydraulic piping. Evaluating the condition of historic buildings should take into account the possibility of this particular phenomenon occurring.

The results shown in Fig. 5–12 and Table 2 and 3. indicate that the subsoil under and around the Basilica building experiences the phenomenon of seepage-induced deformations induced by flowing groundwater. The extent of this phenomenon can be described as suffosion and characterized through a hydraulic gradient value or seepage rate leading to mechanical washing-out of fine soil particles by rainwater and groundwater, which seeps through the soil medium, ultimately leading to soil skeleton collapse and the formation of settlement.

The results of conducted measurements showed that the gradient values within the observation period ranged from 5.3‰ to 8.3‰, and the mean hydraulic gradient for individual soil types found under the building was exceeded within the analysed sections (Fig. 7b). Locally, the closer to P6 the more the hydraulic gradient grows and exceeds critical values, with this gradient exceeded almost threefold in the immediate vicinity of P6 (Fig. 12). Exceeding the gradient for individual soil types can cause the suffosion phenomenon.

Obtained water flow direction visualisations (Fig. 9–12) indicate that the water flow direction in the Basilica building area also changes. Their intensity over such a small area is significant and unnatural. The magnitude of the flow direction changes themselves is important from the perspective of ongoing adverse seepage phenomena in the subsoil.

A detailed deformation analysis involving subsoil around the Basilica building enables formulating a thesis that the subsoil failure algorithm is significantly similar to the situation shown in [7]. The case described in [7] also involved periodic and intensive flows caused by the action of rainwater resulting in seepage-induced deformations and soil parameter changes.

### 3.4. Concepts of design solutions in terms of protecting the basilica building against soil seepage-induced deformations

In practice, the only effective method to protect a building against the development of seepage-induced deformations of the soil is to fully stabilize the water level within the subsoil. This situation is made possible through introducing drainage, most usually external and collection of rainwater to an efficient stormwater drainage system. Constant monitoring of the soil medium hydration level, including stormwater system tightness is also necessary.

It is only partially possible to limit soil seepage-induced deformations in the case of the Basilica building. There is a drainage system around the Basilica main body, which discharges water to a stormwater network through intermediate wells. However, as indicated by the pit excavated in the course of renovation work, the area aroud the building contains numerous non-inventoried drains, originating from different periods, executed at various foundation levels, some of which are patent and enable unobstructed water transport. Groundwater table fluctuations range from 14 (2/7/2019) up to even 274 cm (2/12/2019), which is confirmed by readings taken from the piezometers. The measurements conducted over time indicate that there is not direct correlation between executing construction work in the immediate and indirect vicinity of the Basilica building and the groundwater table level. The piezometer water level clearly rises in the case of intensive rainfall and in spring, i.e., in the period of elevated water level in the nearby Motława Canal. Rainwater flowing from the roof slope is discharged via a drain system to the rainwater drainage network, and the area around the main body of the Basilica is compacted and profiled with an incline towards "the outside" of the building.

## 4. Conclusions

Water level monitoring in the subsoil is very important for building safety, since it may indicate the formation of seepage-induced deformations.

Improper definition of the phenomena ongoing in the subsoil and incorrect application of seepage occurrence criteria may lead to design errors, especially in the case of work associated with reinforcing existing buildings, including historic religious structures.

The (Ultimate Limit State (ULS) in terms of HYD, which applies to failure caused by water flowing through a soil medium, should be obligatorily taken into account when evaluating the technical condition of historic buildings set within an area with groundwater flows.

In the case of the Basilica, cyclic changes of the hydraulic gradients in its subsoil could have initiated seepage-induced deformation in the past, which is reflected in the settling elements of a building like the Basilica, especially the floor in the area of the main body, as well as soil settlement under brick columns, which resulted in their settlement and failure of the ceramic vaults spread over them.

Water level changes in the vicinity should be limited to an absolute minimum or at least maximum values specified by critical gradients in order to protect Basilica structures. Water tables within its contour and inducing flow directly under the Basilica should be stabilized using newly designed drainages.

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## Osiadanie zabytkowego budynku w wyniku deformacji filtracyjnych gruntu

**Słowa kluczowe:** Podłoże budowlane, filtracja w gruncie, osiadanie budynku, deformacje filtracyjne

Streszczenie:

W artykule dokonano przeglądu zagadnień związanych z wpływem przepływu wód gruntowych na właściwości i parametry gruntu, a tym samym na całą konstrukcję posadowionego na nim budynku. Filtracja wody przez grunt, podłoże budowlane lub elementy konstrukcyjne budowli wykonanych z gruntu oddziałuje na szkielet gruntu i może prowadzić do zmian w układzie poszczególnych ziaren względem siebie, czyli do modyfikacji jego struktury. Odkształcenia szkieletu gruntowego wynikające z działania sił filtracji nazywane są deformacjami filtracyjnymi. W artykule scharakteryzowano typowe deformacje wywołane filtracją wody w gruncie oraz podano kryterium określające moment pojawiania się danego zjawiska. W studium przypadku wykorzystano dane dotyczące spękań i odkształceń w zabytkowym budynku oraz filtracji wody w jego podłożu. Na podstawie danych z monitoringu poziomu wody gruntowej przeanalizowano przepływ wód podziemnych i wyznaczono strefy, w których przekroczone zostało kryterium inicjacji procesu sufozji. Wyznaczone strefy pokrywają się z lokalizacją pęknięć i zarysowań budynku i potwierdzają możliwą przyczynę jego uszkodzenia.

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